Clustering at High Redshift
ASP Conference Series, Vol. ???, 1999
A. Mazure, O. Le Fèvre & V. Le Brun, eds

Evolution of the correlation function as traced by the HDF galaxies

Boudewijn F. Roukema[1,2,3]

[1]*Nicolaus Copernicus Astronomical Center, ul. Bartycka 18, 00-716 Warsaw, Poland*
[2]*Institut d'Astrophysique de Paris, 98bis Bd Arago, F-75.014 Paris, France*
[3]*Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune, 411 007, India* (boud@iucaa.ernet.in)

David Valls-Gabaud[4,5]

[4]*UMR CNRS 7550, Observatoire de Strasbourg, 11 rue de l'Université, 67000 Strasbourg, France* (dvg@ast.obs-mip.fr)
[5]*Royal Greenwich Observatory, Madingley Road, Cambridge CB3 0EZ, UK*

Abstract. An initially highly biased value of the spatial correlation function, which decreases with time up to a transition redshift $z_t \sim 1-2$, was predicted theoretically at least as early as 1993, and shown to be consistent with the HDF-N angular correlation function estimates in 1997. Observational analyses are presented here which show (i) an HDF-N estimate of the correlation function amplitude of galaxies selected at $z \sim 2$ (by the UV drop-*in* technique), which supports the estimate $z_t \sim 2$ and (ii) an HDF-N estimate of the correlation function amplitude of galaxies selected at $z \sim 3.7$ by using photometric redshifts, which suggests that the correlation function amplitude evolves as $(1+z)^{2\pm3.5}$ during epochs earlier than z_t.

1. Introduction

The theoretical possibility of an initially highly biased spatial two-point auto-correlation function of dark matter haloes, r_{halo}, which decreases in amplitude as fluctuations in low-density regions successively become non-linear and collapse (decreasing correlation period, hereafter DCP), was noticed at least as early as 1993 (Roukema 1993; Brainerd & Villumsen 1994). Yamashita (unpublished) also noticed the same effect in hydrodynamical N-body simulations, so the effect could follow through to the galaxy correlation function ξ either for the simplest possible star formation hypotheses (e.g. every halo becomes luminous immediately following collapse), or for less simplistic models.

Because implicit estimates of ξ at high redshift via angular correlation function measurements from photometric surveys were *lower* than expected (e.g. Roukema & Peterson 1994 and references therein) in the early 1990's, it seemed

that the DCP would have contradicted the observations. However, Ogawa, Roukema & Yamashita (1997) showed that the HDF-N estimates of the angular correlation function by Villumsen (1997) were *not* in contradiction with the DCP, i.e. that HDF observations were consistent with the DCP.

Since then, high redshift ($z \gtrsim 1$) galaxy spectroscopy via Lyman-break selection and photometric redshift techniques applied (in particular) to the HDF-N (and -S) have created a new era in measurement of galaxy statistics. It quickly became clear that the Lyman-break galaxies, at $z \sim 3$, are highly clustered (Giavalisco et al. 1998) and that the DCP was no longer a mere theoretical prediction.

Several papers further developing the theory of the DCP (Mo & White 1996; Bagla 1998; Moscardini et al. 1998 and references therein) have since appeared, and several observational estimates at $z \gtrsim 2$ have been made and compared to various theoretical predictions (Miralles, Pelló & Roukema 1999; Arnouts et al. 1999; Magliocchetti & Maddox 1999).

In parallel with the various model dependent methods of analysing the observational results, it is suggested that Ogawa et al.'s (1997) extension of Groth & Peebles' (1977) power law model of correlation function evolution via a *transition redshift* z_t and a power law of $(1+z)$ for $z \geq z_t$ should provide a simple way to characterise and compare different observational and theoretical analyses. This is presented in §2.

A complementary observational analysis to the above is that of estimating $\xi(z \sim 2)$, which is done by a method which is itself also complementary to the above: the Lyman-break technique is used to select UV drop-*in* galaxies as opposed to UV drop-*out* galaxies, i.e. those for which $z \lesssim 2.5$. This analysis is summarised in §3., and was carried out using integral constraint corrections *without* reintroducing linear uncertainty terms which formulae like that of Landy & Szalay (1993) are designed to avoid or minimise (§4.).

A high bias was *not* detected at $z \sim 2$. Combination of the Giavalisco et al. (1998) ($z_{\rm med} \approx 3$) and Miralles et al. (1999) ($z_{\rm med} \approx 3.7$) estimates for ξ can then be used to estimate z_t and ν in eq. (1). This is presented in §5.

2. Characterising the DCP

After Ogawa et al. (1997), an extension of Groth & Peebles' (1977) classical formula [Eq. (1) with $z_t \gg 1$] provides a way to represent the observational results without depending on particular galaxy formation models:

$$\xi(r,z) = \begin{cases} \left[\frac{(1+z)}{(1+z_t)}\right]^{\nu} \xi(r,z_t), & z > z_t \\ (r_0/r)^{\gamma}(1+z)^{-(3+\epsilon-\gamma)}, & z_t \geq z > 0 \end{cases} \tag{1}$$

where r is the galaxy pair separation; r and r_0 are expressed in comoving units; $\gamma \sim 1.8$ is determined from observations; ϵ represents low redshift correlation growth and has the value $\epsilon = 0$ for clustering which is stable (constant) in proper units on small scales; z_t is a transition redshift from the DCP at high z to the low z period of correlation growth; and ν represents the rate of correlation decrease at high z [no relation to ν of Bagla (1998)].

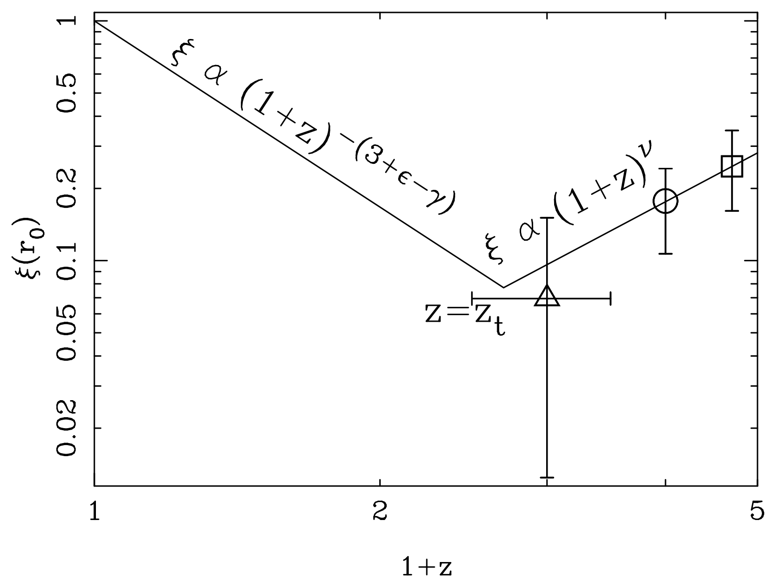

Figure 1. Spatial correlation function evolution as represented in Eq. (1), with $r_0 = 5.5\mathrm{h}^{-1}$ Mpc, and showing observational estimates of Roukema et al. (1999) (triangle), Giavalisco et al. (1998) (circle) and Miralles et al. (1999) (square), and with $\gamma = 1.8$, $\epsilon = 1.4$, $z_t = 1.7$ and $\nu = 2.1$, for $\Omega_0 = 1, \lambda_0 = 0$.

3. The UV drop-in technique: selecting a $z \sim 2$ sample

The UV drop-out technique selects galaxies above $z \approx 2.5$. In contrast, by selecting only those HDF galaxies for which a source is detected in the U (F300W) band, Mobasher & Mazzei (1999) defined a UV drop-*in* sample for which $z \approx 2.5$ was a strong upper limit in redshift. Roukema et al. (1999) used Mobasher & Mazzei's photometric redshift estimations to create a subsample in the range $1.5 \lesssim z \lesssim 2.5$.

Roukema et al. (1999) estimated $\xi(z \sim 2)$ from this sample, finding that for stable clustering in proper coordinates, $r_0 \sim 2.6^{+1.1}_{-1.7}\mathrm{h}^{-1}$ Mpc for curvature parameters $\Omega_0 = 1, \lambda_0 = 0$, or $r_0 \sim 5.8^{+2.4}_{-3.9}\mathrm{h}^{-1}$ Mpc for $\Omega_0 = 0.1, \lambda_0 = 0.9$, if one does not apply any correction for effects of the non-zero size of galaxy haloes on ξ. The correction for possible effects of non-zero halo size is discussed in Roukema (1999).

4. How not to reintroduce linear terms when correcting for the integral constraint

Correlation function estimates in small fields require integral constraint corrections. See §3.1.3 of Roukema et al. (1999) for a discussion and references, in particular Hamilton (1993) for an in-depth analysis.

The following formula from Landy & Szalay (1993):

$$w(\theta) = \frac{N_{gg} - 2N_{gr} + N_{rr}}{N_{rr}} + C \tag{2}$$

where N_{gg}, N_{gr} and N_{rr} are numbers of galaxy-galaxy, galaxy-random and random-random pairs and $C = 0$, avoids linear terms in the uncertainty of the estimate of w (angular correlation function).

However, it follows from Hamilton (1993) that if C is allowed to be a free parameter which is varied in order to match $w(\theta)$ values to a prior hypothesis, e.g. that w is a power law of a given slope, then linear terms are reintroduced.

Without changing the prior hypothesis, the way to avoid reintroducing these terms is to use eq. (24) of Hamilton (1993):

$$w(\theta) = \frac{N_{gg} - 2\overline{n_{\mathrm{est}}}N_{gr} + \overline{n_{\mathrm{est}}}^2 N_{rr}}{\overline{n_{\mathrm{est}}}^2 N_{rr}} \tag{3}$$

where $\overline{n_{\mathrm{est}}}$ is the mean number density, in principle estimated by some means external to the sample, divided by the number density of the sample itself. By treating $\overline{n_{\mathrm{est}}}$ as a free parameter instead of C, the correction is applied optimally.

5. DCP parameter estimates

From Giavalisco et al.'s (1998) estimate $r_0 = 5.3^{+1.0}_{-1.3}\mathrm{h}^{-1}$ Mpc $(\Omega_0 = 1, \lambda_0 = 0)$ at $z_{\mathrm{med}} \approx 3$ and Miralles et al.'s (1999) estimate $r_0 = 7.1 \pm 1.5\mathrm{h}^{-1}$ Mpc at $z_{\mathrm{med}} \approx 3.7$ $(\Omega_0 = 1, \lambda_0 = 0)$, the parameters z_t and ν can be estimated from Eq. (1). These are $z_t = 1.7 \pm 0.9$ and $\nu = 2.1 \pm 3.6$, and are illustrated in Fig. 1. These values are similar to those expected from simulations [§3, §6 of Ogawa et al. (1997); also Fig. 3 of Bagla (1998)], and consistent with the $\xi(z \sim 2)$ estimate which indicates that the DCP has ended by about this epoch.

6. Conclusion

The difficulty in estimating photometric redshifts at $z \sim 2$ can be at least partly overcome by applying the UV drop-*in* technique. This enables studies of galaxy properties at an epoch which appears to be an effective transition epoch between two periods or regimes of galaxy formation, characterised by a minimum in the amplitude of the spatial correlation function.

Further work at this epoch such as that of Martinéz et al. (1999) may therefore provide important clues in understanding galaxy formation.

Acknowledgments. This research has been supported by the Polish Council for Scientific Research Grant KBN 2 P03D 008 13 and has benefited from the Programme jumelage 16 astronomie France/Pologne (CNRS/PAN) of the Ministère de la recherche et de la technologie (France).

Discussion

Judy Cohen: The HDF field subtends a very small angle, so that there are only a small number of galaxies in the field. Doesn't this *scare* you?

B. F. R.: The serious violations of international humanitarian law allegedly carried out in Yugoslavia by the most powerful military coalition on the planet scare me (Rangwala et al. 1999). In contrast, for galaxy two-point auto-correlation function estimates, the conservative use of error bars (e.g. Roukema & Peterson 1994; Roukema et al. 1999) should help avoid undue emotion. The error bars on r_0, z_t and ν are there for a reason, not just for amusement.

References

Arnouts S., Cristiani S., Moscardini L., Matarrese S., Lucchin F., Fontana A., Giallongo E. 1999, MNRAS, accepted (astro-ph/9902290)

Bagla J. S. 1998, MNRAS, accepted, (astro-ph/9711081)

Brainerd T. G., Villumsen J. V. 1994, ApJ, 431, 477

Giavalisco M., Steidel C. C., Adelberger K. L., Dickinson M. E., Pettini M., Kellogg M. 1998, ApJ, 503, 543 (astro-ph/9802318)

Groth E. J., Peebles P. J. E. 1977, ApJ, 217, 385

Hamilton A. J. S. 1993, ApJ, 417, 19

Landy S. D., Szalay A. S. 1993, ApJ, 412, 64

Magliocchetti M., Maddox S. 1999, MNRAS, accepted (astro-ph/9811320)

Martinéz J., Lambas D. G., Valls-Gabaud V. 1999, in ASP Conf. Ser. (this vol), Clustering at High Redshift, ed. A. Mazure, O. Le Fèvre, V. Le Brun (San Francisco: ASP)

Miralles J. M., Pelló R., Roukema, B.F. 1998, submitted, (astro-ph/9801062)

Mo H., White S. D. M. 1996, MNRAS, 282, 347

Mobasher B., Mazzei P. 1999 , ApJ, (submitted)

Moscardini L., Coles P., Lucchin F., Matarrese S. 1998, MNRAS, accepted

Ogawa T., Roukema B. F., Yamashita K. 1997 , ApJ, 484, 53

Rangwala G., et al. 1999, http://ban.joh.cam.ac.uk/∼maicl/

Roukema B. F. 1993, Ph.D. thesis, Australian National University

Roukema B. F. 1999, in ASP Conf. Ser. (this vol), Clustering at High Redshift, ed. A. Mazure, O. Le Fèvre, V. Le Brun (San Francisco: ASP)

Roukema B. F., Peterson B. A. 1994, A&A, 285, 361

Roukema, B.F., Valls-Gabaud, D., Mobasher, B., Bajtlik, S. 1999, MNRAS, 305, 151

Villumsen J. V., Freudling W., da Costa L. N. 1997, ApJ, 481, 578